National Aeronautics and Space Administration

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Flight Dynamics and Controls Discipline Overview

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Objectives and Challenges

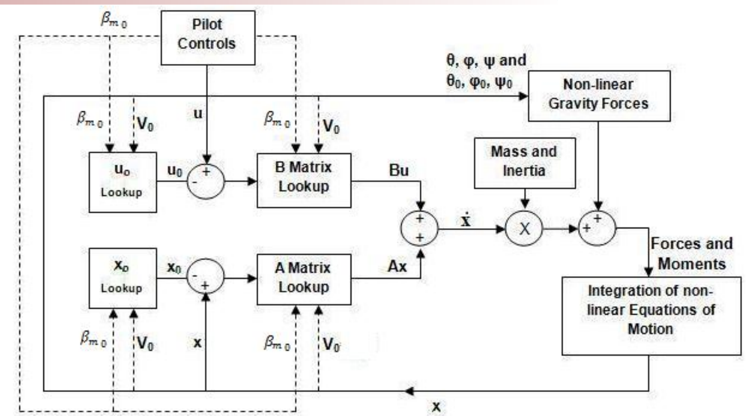
- **Flight Dynamics and Controls deals with the pilot and cockpit technologies as a bridge between the vehicle and operations concepts**
- Flight control of large, complex rotorcraft
  - Implications of large aircraft size
  - Obtaining high bandwidth control
  - Emerging blade control concepts
  - Rotor speed changes
  - Flexible structures
  - Cockpit and pilot inceptors
- Complex flight operations management
  - Hover to cruise to hover conversions
  - Control mode changes
  - Noise abatement
  - Obstacle rich, poor visibility, low altitude operations
  - Congested airspace operations

FD&C Discipline Tasks

- **Control Theory and Intelligent Automation**
  - Full envelope flight dynamics modeling
  - Optimal trajectories for noise abatement
  - Human pilot interface modeling

- **Applied Flight Dynamics and Controls**
  - Handling qualities design envelope requirements
  - Guidance and control for advanced rotorcraft in NextGen airspace
  - Safety analysis of helicopter accidents

Full Envelope Flight Dynamics Modeling



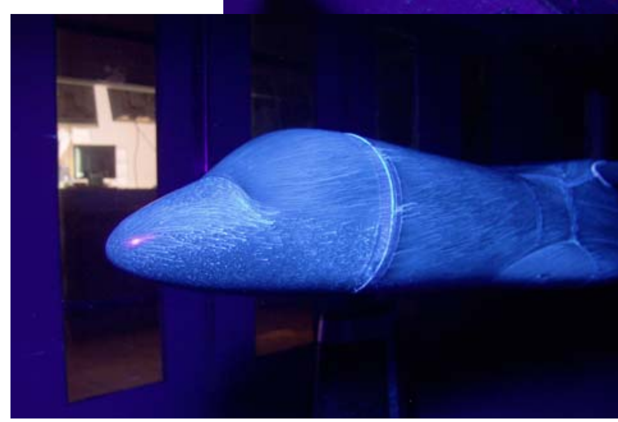
- Simplified hover dynamics model: 2008-2009
- Enhanced low-speed model: 2010-2011
  - Expanded speed envelope
  - Nacelle tilt, independent rotor control

Set of linear models through flight envelope and configuration → **LPV model 'stitching' procedure** → **Continuous bare-airframe model with variations in trim and flight dynamics with flight condition**

- Full flight envelope stability derivative model: 2012-2013
  - Full nacelle range, flaps, rotor speed changes
  - Supports research with modest computational requirements
- Total force and moment model: ~ 2014
  - Higher fidelity physics-based full flight envelope simulation model
- LCTR/HETR test in Army AFDD 7x10 foot wind tunnel at Ames: 2011
  - Measure basic low-speed aerodynamics of fuselage/tail/wing/nacelle

LCTR 7x10-ft Wind Tunnel Test

- First wind tunnel test to measure complete LCTR airframe aerodynamics (without rotors)
- Part of a joint test between NASA and US Army
- Test objectives:
  - Airplane mode (shown) - High speed (200 knots) for lateral-directional airframe stability assessment
  - Helicopter mode - Low speed data (<60 knots) with pitch (+/- 10 deg) and yaw (+/- 180 deg) variations for low speed aerodynamics
- Tasks completed to date:
  - LCTR model installed in the test section
  - Oil flow visualization in airplane mode (shown)
  - Aerodynamic forces and moments measured in airplane mode for three different wingtip/nacelle configurations
- Data to be used for:
  - Comparison/validation of CFD tool predictions
  - Development of flight dynamics simulation models



Optimal Trajectories for Noise Abatement

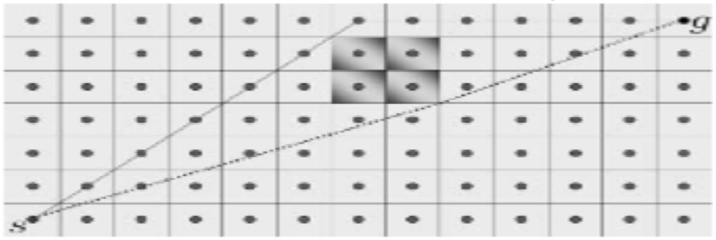
Objective:

- Apply state of the art optimization techniques to design rotorcraft approach techniques that minimize ground noise.

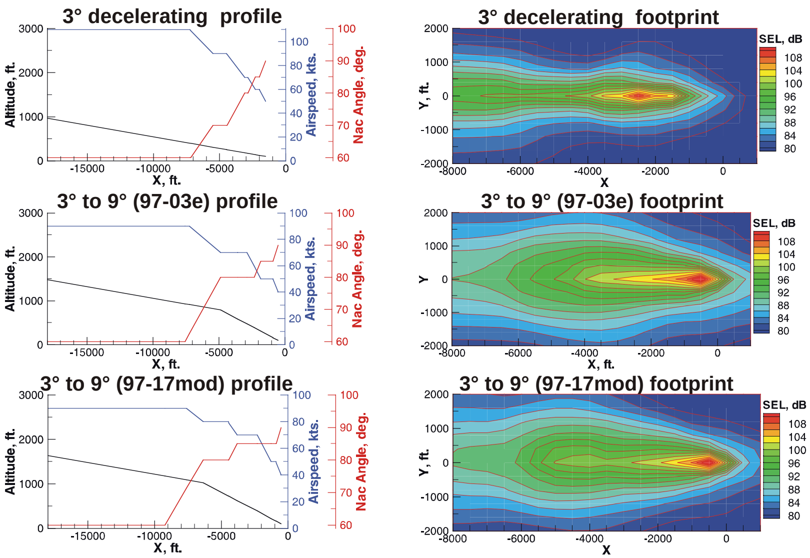
Approach:

- Configuration space for motion planning defines the set of transformations that can be applied to the rotorcraft during approach.
- State of the art constraint optimization and path planning algorithms (A*, Field D*, Probabilistic Roadmaps) search for best trajectories, straight and maneuvers.
- Noise predictions from Rotorcraft Noise Model (RNM) used to evaluate candidate trajectories
- Realistic terrain representations (water, residential, industrial, etc.) allow for solutions that can be applied to real landing environments.

Field D* 3D Path Planning



1999 XV-15 Proposed Approach Profiles



Land Use Model around Pensacola Airport

Optimal Trajectories for Noise Abatement

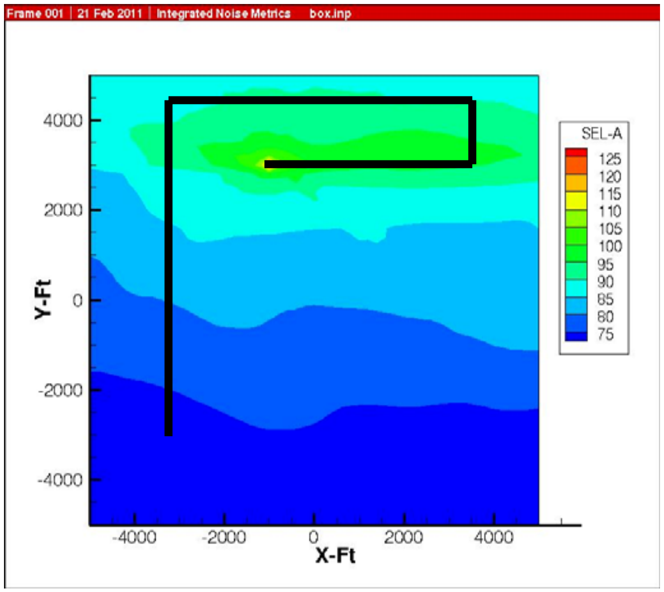
Status:

- Joint work with SRW Acoustics team
- SAA with University of Padua, Italy to develop noise 'cost' functions based on RNM output to be used by optimizer.
- WYE support for developers at Florida Human and Machine Cognition (IHMC) for implementing path planning algorithms, develop land-use models around real airports

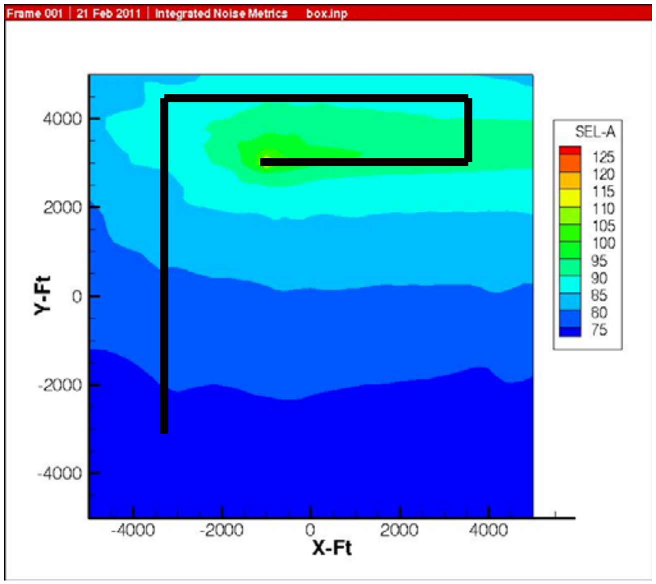
Results:

- Optimizer based on stochastic local search finds trajectories that are roughly 20% quieter on average than 'pilot-defined' quiet paths.
- Pilot-defined 'flyability constraints' means that the optimal trajectories adhere to requirements for safety and passenger comfort.

Baseline height-velocity profile



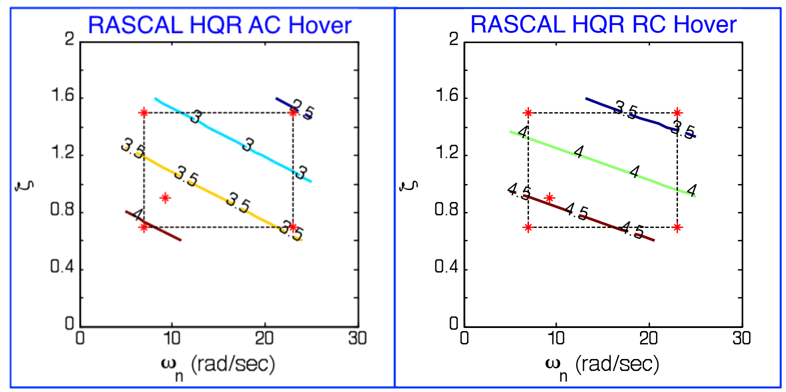
Optimized height-velocity profile



Active Inceptor Handling Qualities Study

- Joint Army-NASA investigation
- Objectives:
  - Study interaction between inceptor force-feel characteristics and handling qualities
  - Investigate flight control system optimization including inceptor characteristics
- Approach:
  - Systematic investigation of varying inceptor force-feel parameters and different types of command response
  - Piloted ground simulation and flight tests
- Current status:
  - Flight tests conducted in 2011 with US Army RASCAL and DLR FHS helicopters
- Next Steps:
  - Piloted simulation experiment at NASA-Ames Vertical Motion Simulator (VMS)

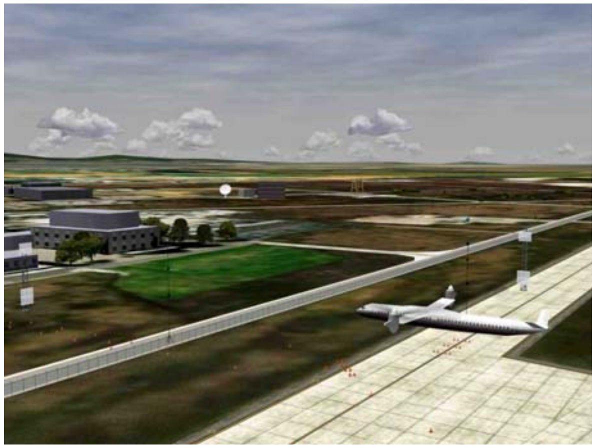
Center Stick Inceptors

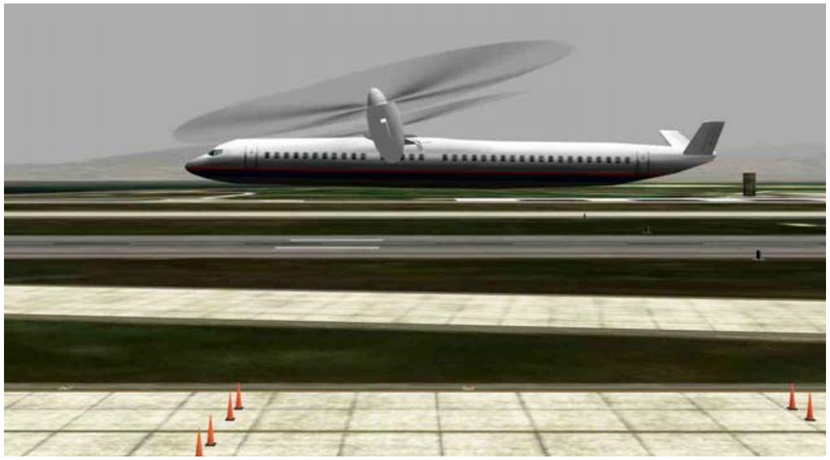


Analysis of gradients shows sensitivity of handling qualities to inceptor damping ratio, but not to the natural frequency.

LCTR2 Handling Qualities Investigations

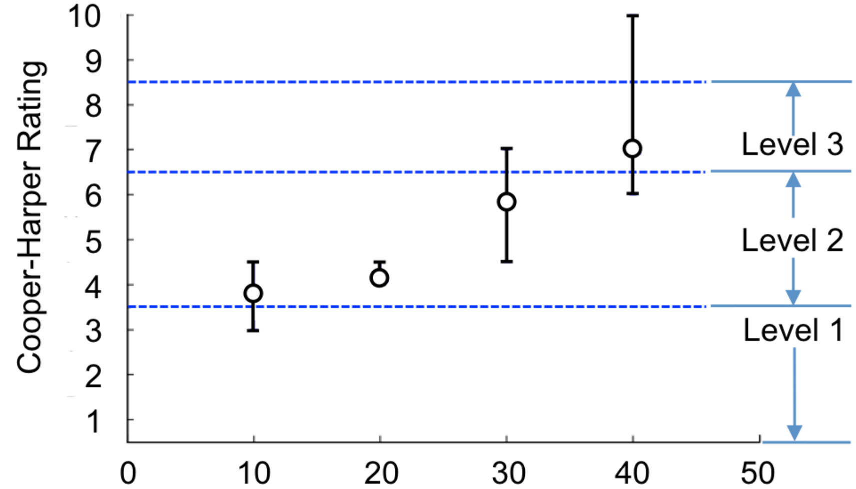
- Objectives:
  - Develop understanding of the flight control and HQ effects of unique characteristics of large helicopters, including tilt-rotors: low bandwidth response, large pilot offset
  - Develop handling qualities and control system requirements for large helicopters
- Approach:
  - Series of experiments to systematically study fundamental Handling Qualities and control system effects throughout flight envelope and airspace integration
  - Piloted simulation experiments in Vertical Motion Simulator (VMS)
  - Partnership with US Army, US Marines and helicopter industry (Bell, Boeing, Sikorsky)
- Current status:
  - Four successful hover and low speed experiments in the VMS (2008 - 2011)

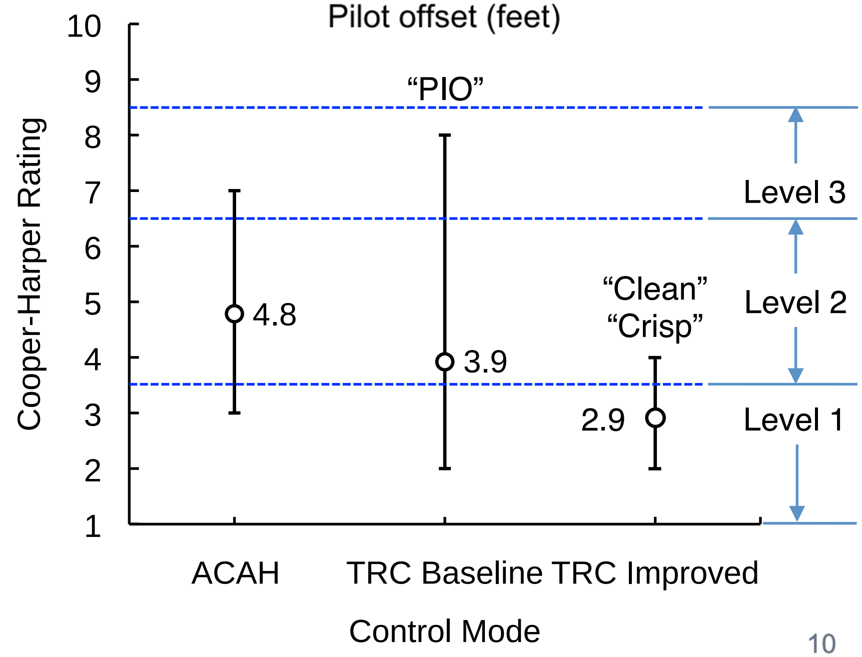




Previous Experiments (2008 -- 2010)

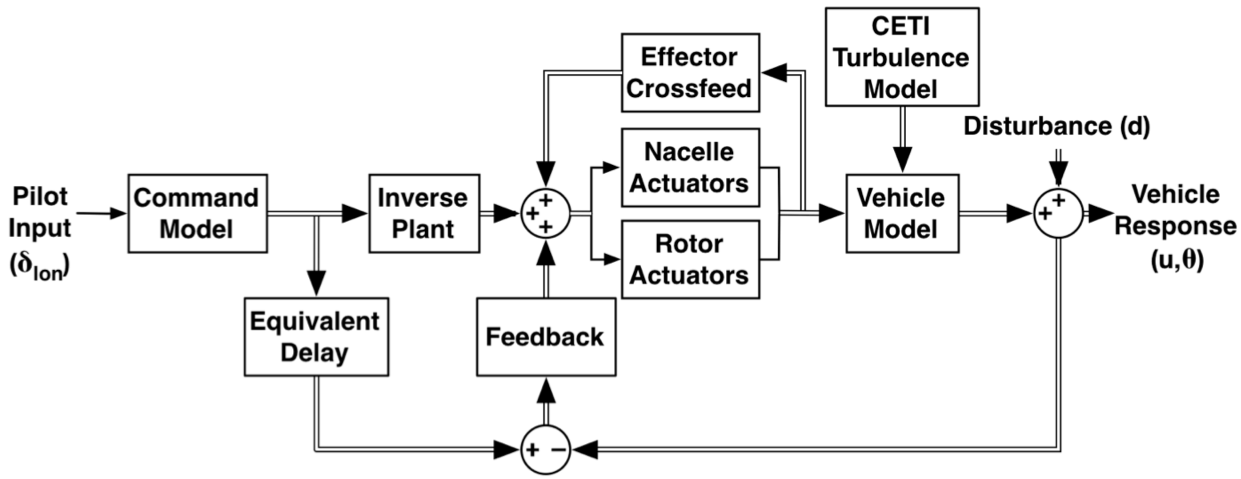
- 2008 – Studied basic effects of rotorcraft size on piloted handling qualities in hover
  - UH-60 Blackhawk, CH-53, and LCTR
  - LCTR only achieved Level 2 Handling Qualities with Attitude Command-Attitude Hold (ACAH)
- 2009 – Investigated fundamental pitch, roll and yaw response requirements and effect of C.G. to pilot offset on handling qualities
  - Level 2 Handling Qualities was best that could be achieved with ACAH control
  - New yaw bandwidth criteria suggested
  - Ride quality degrades due to pitch/heave coupling with larger pilot offsets
- 2010 – Investigated advanced control mode of Translational Rate Command (TRC) using automatic nacelle motion
  - Level 1 Handling Qualities achieved with 'Improved' TRC including nacelle rate cross-feed to longitudinal cyclic
  - Actuator dynamics set at 8 rad/sec





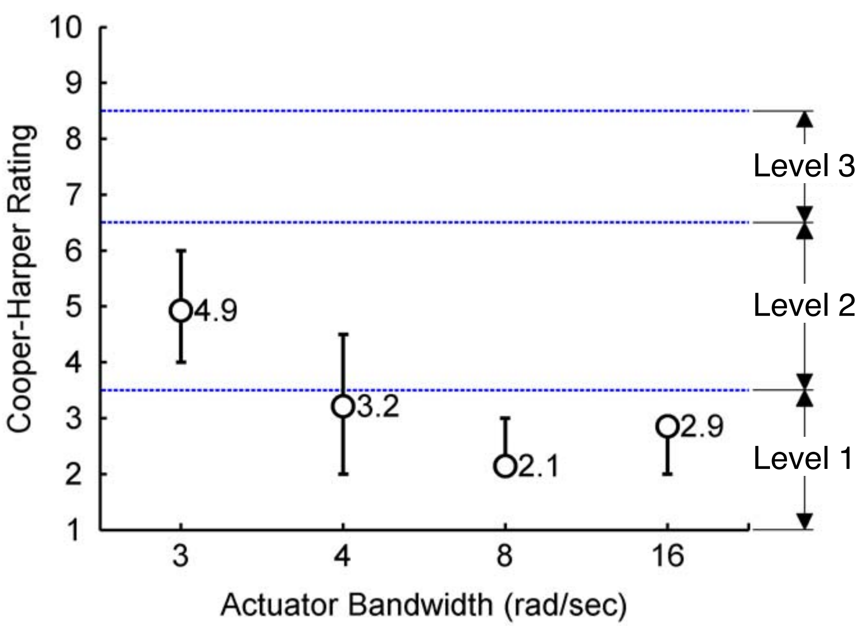
2011 VMS Experiment

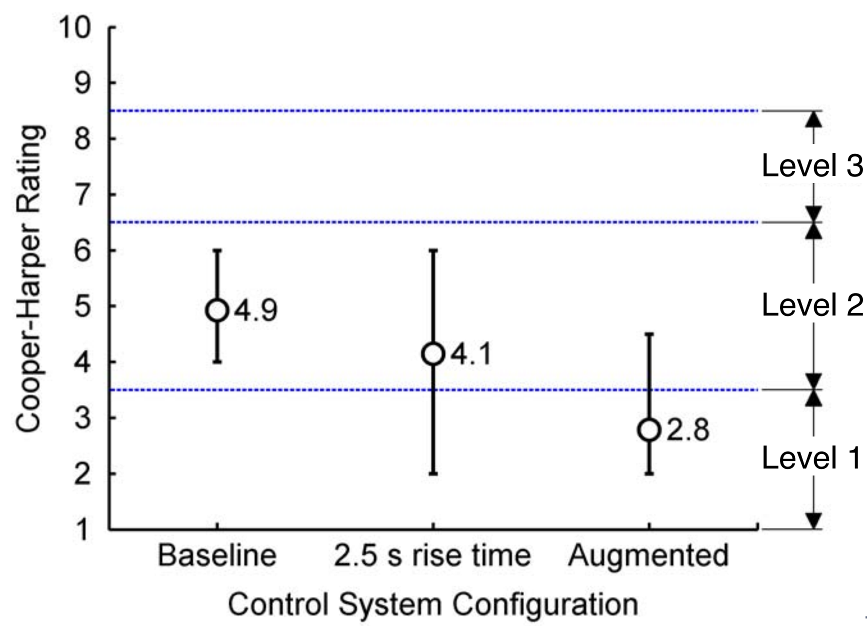
- Objectives:
  - Investigate control allocation between automatic nacelle actuation and rotor cyclic for control redundant tilt-rotor aircraft
    - Automatic nacelle: Low bandwidth
    - Longitudinal cyclic: High bandwidth
  - Investigate nacelle actuation requirements and TRC architectures to achieve Level 1 Handing Qualities
- Approach:
  - Vary nacelle actuator dynamics with TRC architecture from 2010 experiment
  - Investigate alternative TRC architectures to achieve Level 1 Handling Qualities with low bandwidth nacelle actuator



2011 Experiment Results

- Left Figure: Varying nacelle actuator bandwidth (Nacelle-only control)
  - Level 1 HQ achieved with nacelle actuator rates greater than 4 rad/sec
  - Solid Level 2 HQ with 3 rad/sec nacelle actuator bandwidth
- Right Figure: Add feed-forward of velocity command and feedback of velocity error to longitudinal cyclic (3 rad/sec nacelle actuator bandwidth)
  - Level 1 HQ achieved with ‘augmented’ TRC and 3 rad/sec
  - Shows augmenting TRC control architecture can recover Level 1 HQ with lower bandwidth actuators





Concluding Remarks

- Simulation Model Development:
  - Working on full-envelope LCTR physics-based non-linear simulation model for use in piloted-in-the-loop VMS experiments
  - Completing LCTR wing tunnel test in 7x10 foot wind tunnel at Ames to measure basic wing/fuselage/nacelle/tail aerodynamic through flight envelope
  - Continuing development of LPV-based stitched linear model to support flight control and handling qualities research activities
- Trajectory Optimization for Noise Abatement:
  - Joint work with SRW Acoustics discipline including flight test support (Bell 430) and Rotorcraft Noise Model (RNM) in trajectory optimization
  - Currently includes pilot handling qualities and vehicle performance limits and working towards including terrain constraints in trajectory planning
- Cockpit and Pilot Inceptors:
  - Active inceptor handling qualities study jointly with US Army examining interaction between inceptor force-feel characteristics and handling qualities
  - Completed flight tests on US Army RASCAL and DLR FHS helicopters
  - Planning piloted simulation in the NASA-Ames Vertical Motion Simulator (VMS)

Concluding Remarks

- Handling Qualities Design Envelope Requirements:
  - Completed 4 VMS entries examining basic low-speed handling qualities of large rotorcraft
    - Developed basic understanding of effect of vehicle size on handling qualities
    - Suggested new design requirements for large rotorcraft handing qualities
    - Examined advanced control modes including TRC with automatic nacelle control
    - Explored control redundancy to improve handing qualities
  - Working on a summary report combining results of 4 experiments

- Future Work in Handling Qualities:
  - Define follow-on experiments in the VMS
    - Trajectory optimization for noise abatement
    - Guidance and control of advanced rotorcraft in NextGen
  - Develop basic handing qualities analysis in preliminary design / sizing phase with tools such as NDARC
  - Develop higher fidelity handling qualities scale as an addition to Cooper-Harper handling qualities ratings scale

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